If It Quacks Like a Comet...

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Abstract

Some researchers have interpreted the failure to detect gas emission in the coma of Comet Shoemaker-1 .evy 9 as evidence that the S1.-9 fragments were not active as they orbited Jupiter. Detailed thermal modeling of the cometary fragments is performed to show that the expected gas production rates arc well below the upper limits set by observers. Thus, the comet could easily have been active. Additional evidence is provided to suggest that the comet fragments were indeed active. Comet Shoemaker-1.cvy 9 was a comet.

Introduction

Telescopic observations of the fragments Of Comet Shoemaker-Levy 9 following their discovery and prior to their impacts with Jupiter, failed to detect any evidence of gas emission from the cometary nuclei (Weaver et al., 1994, 1995; Cochran et al., 1994; Stüwe et al., 1 995). Some researchers (e.g., Sekanina et al. 1994; Sekanina, 1995) have interpreted these observations as evidence that the comet fragments were not active, that is, they were not actively sublimating ices and carrying dust into the cometary comae. These assertions are incorrect, as will be shown below.

No formal definition of what constitutes an active comet exists, though several have been offered in the literature. One of the most basic is that offered by Weissman et al. (1989) which defines an active comet as "a comet losing volatiles in a detectable coma." This definition is the one typically accepted by observers, and is used to classify objects upon their discovery. Alternative definitions of a comet usually involve the physical nature of the body, i.e., the existence of a substantial amount of ice in the body that can result in a coma if the body comes Close enough to the sun.

The fragments of Comet Shoemaker-Levy 9 displayed visible comae at their discovery (Shoemaker et al., 1993) and throughout their orbit around Jupiter. The unanswered question is whether those comae were the result of active sublimation from the cometary fragments, or whether they were the result of debris liberated during the tidal disruption of the progenitor nucleus of the comet in July, 1992.

Observations with the Faint Object Spectrograph on the Hubble Space Telescope (11ST) on three different occasions (July 1, 1993; March 28-30, 1994; July 14, 1994) set upper limits on OII production rates from the Q 1 and G fragments of Comet Shoemaker-Levy 9 of -1 to 2 x 1027 See-'. Cochran et al. (1 994) placed their spectrograph slit along the line of nuclei, observing all 21 on two occasions in February and March 1994. 'J'heir upper limits, summing the observations, were 8.4 x 1026 sec^{-1} for 01 I and 1.4 x 1024 See"' for CN (the upper limit for CN includes a third observing date in April 1994). Observed OII production rates in comets are typically a factor of 500 to 103 times that for CN. Stüwe et al. (1995) observed S1,-9 fragments K, I., 1', Q, and S on July 1-2, 1994 and set upper limits on CN production rates for each fragment of 1.8 to 2.8 x 1023 sec^{-1}.

This paper presents theoretical modeling and other arguments which show that Comet

Shoemaker-Levy 9 was active and was sublimating volatiles while it was under observation in 1993-94. The 3-dimensional comet thermal model presented here is far superior to the simple, 1-dimensional slow-rotator model used by Weaver et al. (1995), including such important features as body shape and orientation, diurnal heating and cooling, and surface heat flow. Section 2 of this paper presents results of applying the thermal model to icy comet fragments in the orbit of Comet Shoemaker-Levy 9. Section 3 discusses other observations which support the hypothesis that the comet was active, and also the errors in arguments presented against activity by other researchers. Section 4 summarizes and discusses the results.

Thermal Modeling

The SL-9 comet fragments were modeled using the comet thermal model of Weissman and Kieffer (1981, 1984a), called KRC. This computer-based model treats the nucleus as a 3-dimensional water ice sphere in heliocentric orbit, with the nucleus radius, albedo, rotation axis orientation, and rotation period specified by the user. Thermo-physical properties of the nucleus' icy-conglomerate surface are also provided by the user. The model assumes uniform surface properties on the nucleus surface and versus depth beneath the surface. integration around the comet's orbit is accomplished in uniform time steps of 5 or 10 days. At each orbital step, the energy balance and heat diffusion equations are solved for all points on a latitude-longitude grid on the nucleus surface, and over several complete rotations of the nucleus.

The energy balance equation is solved iteratively with temperature as the independent variable. For the heat flow, the program uses an explicit finite-difference scheme with layer thickness increasing exponentially downward. The time step size (initially 1/384th of a rotation period) progressively doubles at various lower depths where allowed by convergence criteria. The lower boundary condition can be chosen as either insulating (no heat transport), or isothermal (constant T).

For a typical fragment of Comet Shoemaker-Levy 9, two hypothetical scenarios were investigated. The first scenario attempted to simulate a typical cometary nucleus. It assumed an albedo of 0.04 (Keller et al., 1986) and thermal inertia of 0.003 cal cm^{-2} K^{-}' $sec^{-1/2}$, as found for periodic Comet Halley by Weissman (1987). Other thermo-physical parameters were also chosen similar to Comet Halley. A modest nucleus obliquity of 25° was assumed, with a rotation period of 24 hours. The second scenario was designed to maximize the possible insolation going into

sublimation of surface ices. It assumed a non-rotating nucleus with albedo = 0, no heat flow into the interior (thermal inertia = O), and with the rotation pole of the comet pointed at the Sun.

The heliocentric orbit of Comet Shoemaker-1.evy 9 was kindly provided by D. Yeomans (personal communication). The results of the simulations shown below arc for the position of the comet fragments on July 1, 1993, the date of the first HST FOS observations. The KRC program was run for eight orbital time steps of 10 days each prior to that date, to insure numerical stability of the resulting thermal model.

Results of the computer simulations, plotting expected water production rates versus fragment radius, arc shown in Figure 1. The typical comet scenario is depicted by the solid sloping line, while the maximum sublimation scenario is depicted by the dashed sloping line. The horizontal dot-dashed line is the Cochran ct al. (1994) upper limit on OH production of 0.84 x 1027 See''', Assuming the typical comet model, the upper limit on the effective nucleus radius is -42 km. Even assuming the maximum sublimation model, the Cochran ct al. observations place an upper limit on the effective nucleus radius of -7.5 km.

These upper limits can be compared with estimates of the size of the S1.-9 fragments from various observers. Scotti and Melosh (1993), Asphaug and Benz (1 994), and Solem (1994) all estimated maximum radii for the progenitor comet of 0.75 to 1.0 km, which resulted in the largest fragments having radii of -0.25 km. At the other extreme, Weaver ct al. (1 995) using HS''1', estimated upper limits to the fragment radii of 0.3 to 2.1 km, though they noted that much smaller radii for the larger fragments, of -0.5 km could not be ruled out. Summing over all fragments, their results suggests an upper limit on the radius of the progenitor nucleus of -3.8 km, Sekanina ct al. (1 994) found a progenitor nucleus radius of 5.1 km.

All of the estimates of the size of the progenitor nucleus arc less than the upper limit provided by the maximum sublimation model. However, breaking the comet into multiple fragments greatly increases the surface area available to sublimation. If one assumes that the original nucleus was reassembled into 21 equal-sized fragments, then each fragment had a radius equal to $21^{1/3} = 0.36$ times the original radius. The total surface area of the 21 nuclei would be 2.8 times that of the original nucleus. Assuming the typical comet thermal model, the Cochran ct al, (1994) OH upper limit implies an upper limit on the average fragment radius of 9.1 km, more than four times the largest fragment size estimate by Weaver et al. (1 995). For the maximum sub] i mat ion thermal model, the corresponding average radius is 1.6 km, somewhat less

than the upper limit found by HST for the largest nuclei.

'l'bus, the upper limits on the observed OH production from the fragments of Comet Shoemaker-l .evy 9 arc not in conflict with expected water production rates from icy fragments at the comet's solar distance, unless one assumes that the HST upper limits for the radii of the fragments arc correct, and that all the fragments were sublimating at their maximum possible rate. It seems very unlikcl y that both circumstances exist, in particular since the maximum sublimation model represents an unphysical situation.

The CN limits found by Cochran et al. (1 994) are consistent with the conclusion above, but the limits by Stüwe et al. (1995) set tighter limits on the sizes of the individual fragments. Assuming an 01 I/CN ratio of 103, Stüwe ct al.'s upper limits on CN suggest gas production rates a factor of -4 lcss than the 011 upper limits. This suggests that the upper limit on the average nucleus radius is a factor of two lcss than the values given above. Using the typical comet thermal model, this implies a radius of 4.5 km, still a factor of two more than the largest HST upper limit radii cst i mated by Weaver ct al. (1995). Using the cxtrcmc comet model, the average nucleus radius would have to have been less than ~ 0.8 km. Since the maximum sublimation model rcprcscnts an unphysical situation, this is not a cause for conccrn.

We conclude that the observed upper limits on 011 anti CN production from the Shoemaker-l .cvy 9 fragments do not constrain the estimated sizes of the fragments. l'bus, the negative detections of 01 I and CN cannot bc used to rule out activity in the comet fragments, as was erroneously done by Sckanina et al. (1 994). It is worth noting that the largest fragment radii suggested by impact modelers (Takata et al., 1994; Boslough ct al., 1995) arc on the order of 1 to 1.5 km, much smaller than Sekanina ct al's. (1994) estimates. Somewhat smaller radii of -0.25 km were suggested by Zahnle and Mac Low (1994).

Cometary Activity

A simple argument in favor of ongoing activity in the Shoemaker-Levy 9 fragments was presented by Weaver ct al. (1995), who noted that the comae around the fragments remained essentially spherical throughout the 1.3 years that the comet was under observation, until the last fcw weeks before impact. The dimensions of the comae, typically $\sim 10^4$ km in radius, greatly exccedcd the gravitational spheres of influence of their central nuclei, which are on the order of -100 nuclcus diameters. If the comae were composed of large particles liberated during the tidal

disruption of Comet Shoemaker-Levy 9 in July 1992, then the particles should have pursued independent orbits around Jupiter. The particles within each coma would have been stretched into a bar-like structure by Keplerian shear, just as the entire string of nuclei was. Such bar-like structures arc actually seen in the 1 RAS meteoroid dust trails for other short-period comets (Sykes et al., 1986) extending down to particles as small as 100 μm. These bar-like structures should already have been evident when the comet was discovered in March 1993, and should have grown substantial y over the ensuing months.

The failure to observe bar-like structures for the comae is evidence that they were not composed predominantly of large particles. If the Shoemaker-Levy 9 comae were composed of much finer particles liberate.d during the tidal disruption event, they would have been blown away by solar radiation pressure well before the comet was discovered. '1'bus, the material in the comae must have been continuously resupplied for them to maintain their near-spherical shapes.

Sckanina et al. (1994) and Sckanina (1995) argued that the orientation of the observed dust tails of the SL-9 fragments is additional evidence of the lack of activity. They claimed that the orientation of the tails should have changed as the line-of-sight from the Earth passed through the projected Sun-comet vector due to the Earth's orbital motion. This argument ignores the fact that comet tails arc not precisely anti-solar, in particular, Type II dust tails lag the anti-solar vector by a substantial angle due to Keplerian shear as the dust grains move outward from the **Sun. in** addition, because the viewpoint from the Earth was close to the Sun-comet line, the tails were substantially foreshortened and changes in their relative orientation were difficult to detect.

Study of other comets support the likelihood that the fragments of Shoemaker-Levy 9 were active. Comet Halley was observed to display visible coma at ~5.8 AU inbound in late 1984 (Spinrad and Djorgovski, 1984). This is the same distance that Weissman and Kieffer (1984b) predicted that sub-micron dust grains could be first lifted off the nucleus surface by water ice sublimation. Wyckoff et al. (1985) failed to detect CN emission from Halley at 5.60 AU in November 1984, but did detect CN production of 3×10^{24} scc^{-1} at 4.84 AU in February 1985.

Another example of an active comet at Jovian distances is the well-known object, P/Schwassmann-Wachmann 1. This comet displays sporadic activity completely around its orbit, and CO was recently detected in its coma at radio wavelengths (Senay and Jewitt, 1994). SW-1 is in an orbit similar to one of the two possible precursor orbits for the Shoemaker-Levy 9

progenitor, prior to its capture into orbit around Jupiter (Benner and McKinnon, 1995).

Observations of other comets also demonstrate activity at solar distances comparable to or greater than Jupiter. Dynamically new long-period comets such as Kohoutek (1973 X11) or Bowell (1 982 I) often display substantial activity at 4-8 AU on the inbound legs of their orbits. A number of explanations have been suggested for the source of this activity. Whipple (1978) proposed that comets may be covered with a frosting of volatile molecules collected during the comets' long storage in the Oort cloud. This material would warm and sublimate on the first perihelion passage as the comet approached the Sun, and could thus explain the substantial dimming of dynamically new comets often seen following perihelion. Prialnik and Bar-Nun (1987) showed that conversion of amorphous ices to crystalline ices would occur in dynamically new comets for the first time at about 5 AU inbound as the comet first approached the Sun. Subsequent conversions would occur at about 8 AU outbound because of the time required for the perihel ion thermal wave to penetrate to the buried amorphous ice interior. Finall y, solar heating can cause ices more volatile than water ice to sublimate and diffuse out of the cometary interior (Espinasse et al., 1991).

This latter mechanism is likel y very important for Comet Shoemaker-Levy 9. The tidal breakup of the original nucleus would have exposed large quantities of volatile ices (more volatile than water) previously buried in the cold, deep interior of the progenitor nucleus. These ices would have provided a large volatile source in the days immediately after the comet's disruption, and would cent inuc to di ffuse out of the near-surface layers throughout the brief dynamical lifetime of the fragments. 'l-hc slow decay in activity observed for the S1 ,-9 fragments may have been a result of the slow decay of the supply of these near-surface volatiles.

Many long-period comets have been followed to heliocentric distances well beyond 10 AU and appear to display substantial activity on their outbound legs (Meech, 1993). These observations may not be as relevant to the problem considered herein, since they deal with long-period comets which arc dynamically younger than SL-9 and presumably much "fresher" in terms of fewer perihel ion passages and greater volat i le content.

Discussion

Small bodies in the solar system arc typically classified at discovery as asteroids or comets depending on the presence of visible coma at the time of discovery. The classification is made

within any attempt to verify if the comet is indeed active, versus an object surrounded by a static dust cloud. No asteroidal objects have ever been observed to display visible coma.

This procedure has occasionally led to confusion at later times when asteroidal objects began to display cometary coma. The best known example is 2060 Chiron (Kowal et al., 1979), which was likely discovered during a cometary outburst that was largely discounted by observers. Subsequent observations clearly showed that Chiron is a comet and it is now included in both the comet and asteroid catalogs. A somewhat different case is periodic comet Wilson-Barrington which was discovered as a comet but whose orbit could not be firmly established. It was then independently rediscovered and classified as asteroid 4015. Bowell and Marsden (1992) were able to show that the two objects were one and the same. Other transitional objects are the low activity periodic comets Arend-Rigaux and Neujmin 1 (Marsden, 1970), and likely some of the Earth-crossing asteroids (e.g., 2201 Oljato, 3200 Phaethon; Weissman et al., 1989).

It is thus interesting and somewhat amusing that some researchers, both observers and theorists, have chosen to question the classification of Comet Shoemaker-Levy 9 as a comet, based solely on its physical appearance. They require confirmation of its volatile content through spectroscopic observations. However, the fact that such observations are difficult and have resulted only in upper limits on volatile production, cannot be used to rule out cometary activity. It is surprising that some researchers do not seem to understand the meaning of upper limits. Also, it is interesting that those who interpret the upper limits on the SL-9 gas production rates as implying no gas production, seem to be the same individuals that interpret the HST upper limits on the sizes of the fragments as the true sizes of the fragments.

The evidence presented herein shows that all observations of comet Shoemaker-Levy 9 are consistent with the nucleus fragments being active, and fail to provide any evidence that they are not

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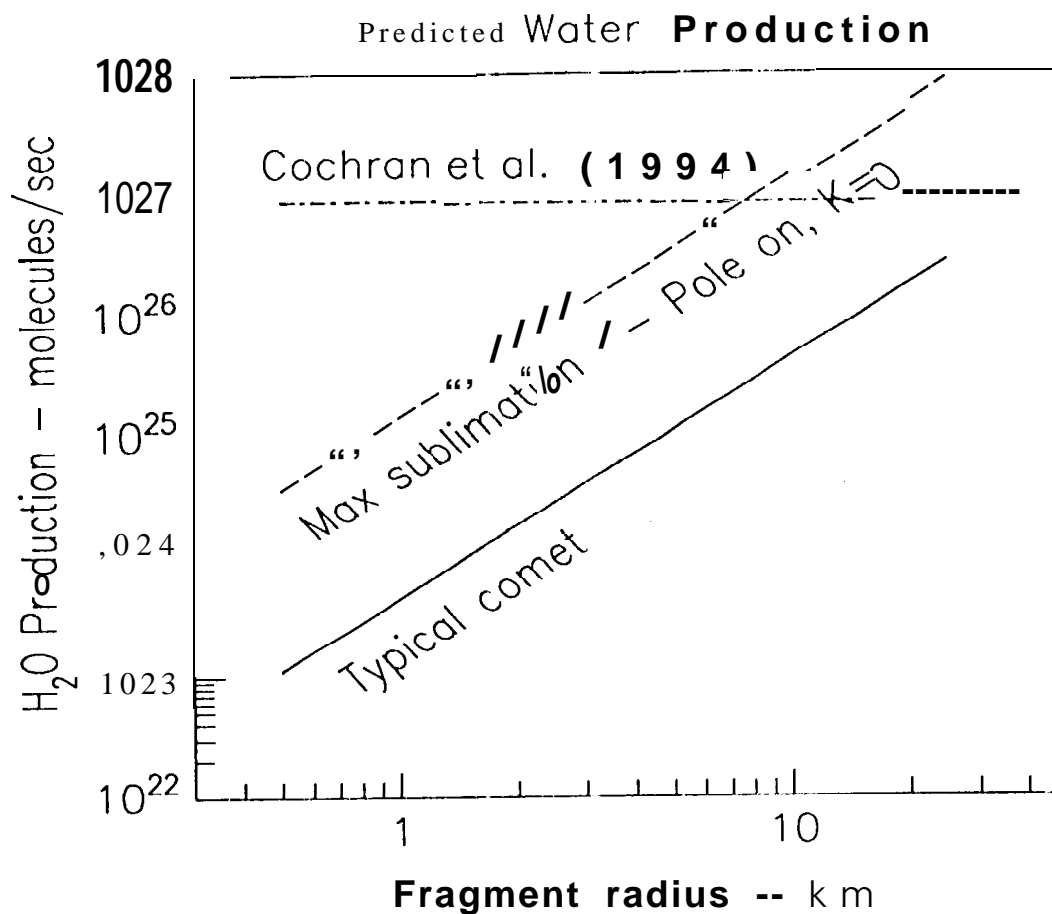Zahnle, K., and Mac Low, M.-M. 1994. The collision of Jupiter and comet Shoemaker-Levy 9. *Icarus* 108, 1-17.

Figure 1. Gas production rates for hypothetical water ice nuclei in the orbit of Comet Shoemaker-Levy 9, as a function of nucleus radius. Two scenarios arc assumed: 1) a typical cometary nucleus with thermo-physical properties similar to that for Comet Halley (solid line), and 2) a non-relating water ice comet with zero albedo, zero surface heat flow, and nucleus rotation pole pointed directly at the Sun (dashed line). The latter scenario, although physically unrealistic, maximizes the possible sublimation from the cometary nucleus. The horizontal dot-dashed line is the 011 upper limit for the fragments of Comet Shoemaker-I. evy 9 of 0.84 x 1027 sec^{-1} as found by Coc.bran et al. (1 994).